REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
30 June 1995

3. REPORT TYPE AND DATES COVERED
Final Report 1 July 1994 - 30 Dec. 1994

4. TITLE AND SUBTITLE
Wideband Photonic Crystals

5. FUNDING NUMBERS
ARO 157-94

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
33112-PH

11. SUPPLEMENTARY NOTES
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
This report summarizes two technical approaches aimed at developing three-dimensional photonic crystals having wider stop bands than conventional crystals. The first approach is a composite photonic-crystal made by stacking monoperiodic sections of a (111)-oriented fcc crystal. Because of its similarity to heteroepitaxial structures made from semiconductors having different band gaps, we call it a photonic-crystal heterostructure. By making a discrete change in the lattice constant between adjacent monoperiodic sections, the net stop-band width can be increased well beyond that of a given section. In a stack of three different sections each having one fcc repeat-unit, a stop band was measured between approximately 17 and 26 GHz which gradually increased in depth with frequency. The second approach is a metallodielectric photonic crystal fabricated by placing metal spheres at each lattice site of a dielectric face-centered-cubic structure. The resulting sample displays an electromagnetic stop band spanning approximately one octave. The lower-frequency edge of the stop band is consistent with the Mie condition for the metallic spheres, and the center frequency of the stop band depends on the periodicity of the lattice and the support dielectric material. For example, a sample having a cubic lattice constant of 1.65 cm, 3/8-inch-diameter chrome spheres at each atomic core, and Teflon support dielectric displayed a lower band edge of approximately 5.2 GHz, an upper band edge of about 12.8 GHz, and a maximum rejection at the center of the band of roughly 20 dB.

14. SUBJECT TERMS
Bravais Lattices, Photonic Crystals, Electromagnetic Stop Bands
Bragg Scattering, Mie Scattering

15. NUMBER OF PAGES
23

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

WIDEBAND PHOTONIC CRYSTALS

FINAL REPORT

ELLIOTT BROWN

6 JULY 1995

U.S. ARMY RESEARCH OFFICE

ARO-157-94

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1. INTRODUCTION

1.1. Summary of technical concepts and accomplishments

This is the final report for the program entitled "Wideband Photonic Crystals," which was undertaken at Lincoln Laboratory from 1 January 1994 through 30 December 1994. The primary goal of this program was to investigate new types of photonic-crystal structures that could provide much wider stop bands than conventional crystals. The first one investigated was a composite structure made by stacking sections of monoperiodic face-centered-cubic (fcc) crystals having different lattice constants. The design strategy was to make the stop bands in adjacent sections nearly contiguous in frequency. In a stack of three different sections each having one fcc repeat-unit, a stop band was measured between approximately 17 and 26 GHz which gradually increased in depth with frequency. In many ways, this stack is the electromagnetic analog of a semiconductor heterostructure, and is thus called a photonic-crystal heterostructure in this report.

The second structure was a metallodielectric photonic crystal (MDPC) consisting of a monoperiodic fcc lattice having metallic spheres at each atomic site. In devising this structure, it was hypothesized that the limitation of conventional (i.e., all dielectric) photonic crystals is that the "atoms" exhibit a large amount of forward scattering in addition to back scattering. This is because radiation can always propagate through a dielectric material as dictated by Maxwell's equations. Rapid progress was made in the MDPC investigation by using the same fcc dielectric structures as in the photonic-crystal heterostructures and simply placing a metal ball bearing at each lattice site. In MDPC samples having just one repeat unit of the fcc crystal, stop bands were measured that had a width of approximately 1 octave and a depth of 20 dB.

An important by-product of this program was the delivery to the Army Research Laboratory (Dr. Louis Jasper) of a prototype MDPC sample for operation at L band (1 to 2 GHz). The MDPC structure was chosen over the heterostructure because of its compact size and high rejection per unit lattice constant. The resulting sample is discussed in detail in Sec. 3.2.

1.2. Motivational background

To justify the technical approach taken in this program, it is helpful to review conventional photonic crystals. In general, they are periodic dielectric or metallic structures that display a stop band in their electromagnetic transmission characteristics. If this stop band is omnidirectional, then the photonic crystals have a band gap in their three-dimensional ω-k dispersion relation. Such photonic crystals are uniquely suited to microwave and millimeter-wave applications requiring a three-dimensional stop band because conventional materials and components can not meet this requirement.

The first photonic crystal to exhibit a three-dimensional stop band was a face-centered-cubic (fcc) structure with nonspherical air atoms. The crystal was fabricated at Bellcore from the synthetic dielectric material Stycast [1], and displayed a band stop in the microwave range between 13 and 16 GHz. More recently, it has been shown that superior band-stop characteristics can be obtained from the diamond crystal structure, and that such a crystal can be fabricated by stacking dielectric rods in a "woodpile" structure [2,3]. The technique of silicon micromachining has enabled the fabrication of diamond photonic crystals having stop bands up to 450 GHz [4].

At Lincoln Lab an fcc structure has been constructed by stacking two-dimensional triangular-lattice slabs containing cylindrical air atoms [5]. The vertical repeat unit comprises three layers (A,B,C) in which the middle layer (B) is stacked below the top layer (A) in such a way that each atom lies directly below the center of a triangle in (A). The bottom layer (C) is aligned so that its atoms lie directly below the remaining triangles in (A). The top view of this stacking arrangement (ABC) is shown in Fig. 1. If the atoms were spherical and there was no intervening dielectric material, this stacking arrangement would result in the (111)-oriented face-centered cubic (fcc) close-packed lattice [6]. The (111) fcc lattice results from the arrangement of Fig. 1, provided that the triangular lattice constant t is related to the slab thickness s by $t = (3/2)^{1/2}s$. The fcc conventional cubic lattice constant a is then given by $a = 2^{1/2}t$.

Shown in Fig. 2 are the microwave transmission spectra through 1 to 4 repeat units of the fcc crystal for radiation incident along the [111] direction. While the transmission drop associated with a stop band appears with just one repeat unit, the precipitous edges associated with a stop band do not appear until there are 3 repeat units. Physically, this reflects the fact that three is the minimum number for which one repeat unit is bulk-like in the sense that it is surrounded by identical material. The stop band occurs between roughly 17.0 and 18.7 GHz, corresponding to a stop-band width of 9.5% about the center frequency. The maximum rejection associated with this stop band is roughly 40 dB. This corresponds to approximately 6 dB of rejection per cubic lattice constant.

While the Lincoln-Lab fcc structure has an inferior stop band compared to the Bellcore and diamond woodpile crystals, it has great advantages in terms of ease of manufacture and ruggedness. It is readily made by stacking one type of dielectric slab, each slab having cylindrical holes made by drilling or boring *perpendicular* to the plane of the slabs. In contrast, the Bellcore crystal requires three times as many holes through each atomic site, each hole oriented at the precise angle of 35.4° away from the normal. The diamond woodpile structure requires a tedious manual stacking of dielectric rods. The Lincoln fcc crystal is also more rugged than the other structures because the thin walls between adjacent atoms are oriented vertically with respect to the top surface.

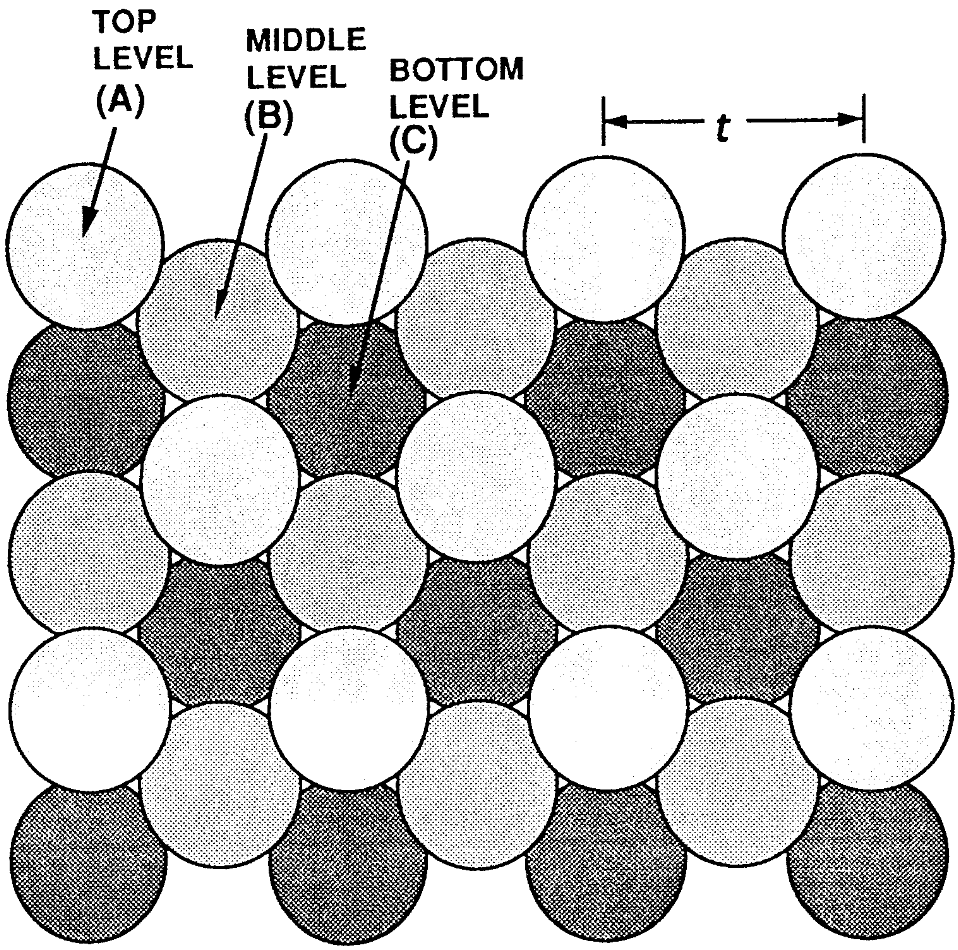

Fig. 1. Top view of Lincoln Laboratory (111)-oriented photonic crystal. The shaded circles represent the cylindrical atoms in three successive layers of the fcc repeat unit.

2. PROGRAM OBJECTIVE AND TECHNICAL APPROACH

While the above crystal structures are important scientifically, they have the limitation that the width of the stop band is limited to about 20% of the center frequency. Several of the microwave applications envisioned for the photonic crystal require operation over a much broader range of frequency than 20%. This is particularly true for the new class of antennas required in wideband radar and communications systems, which will require an operating bandwidth of one octave or more. This is the primary reason that the present program was proposed and carried out.

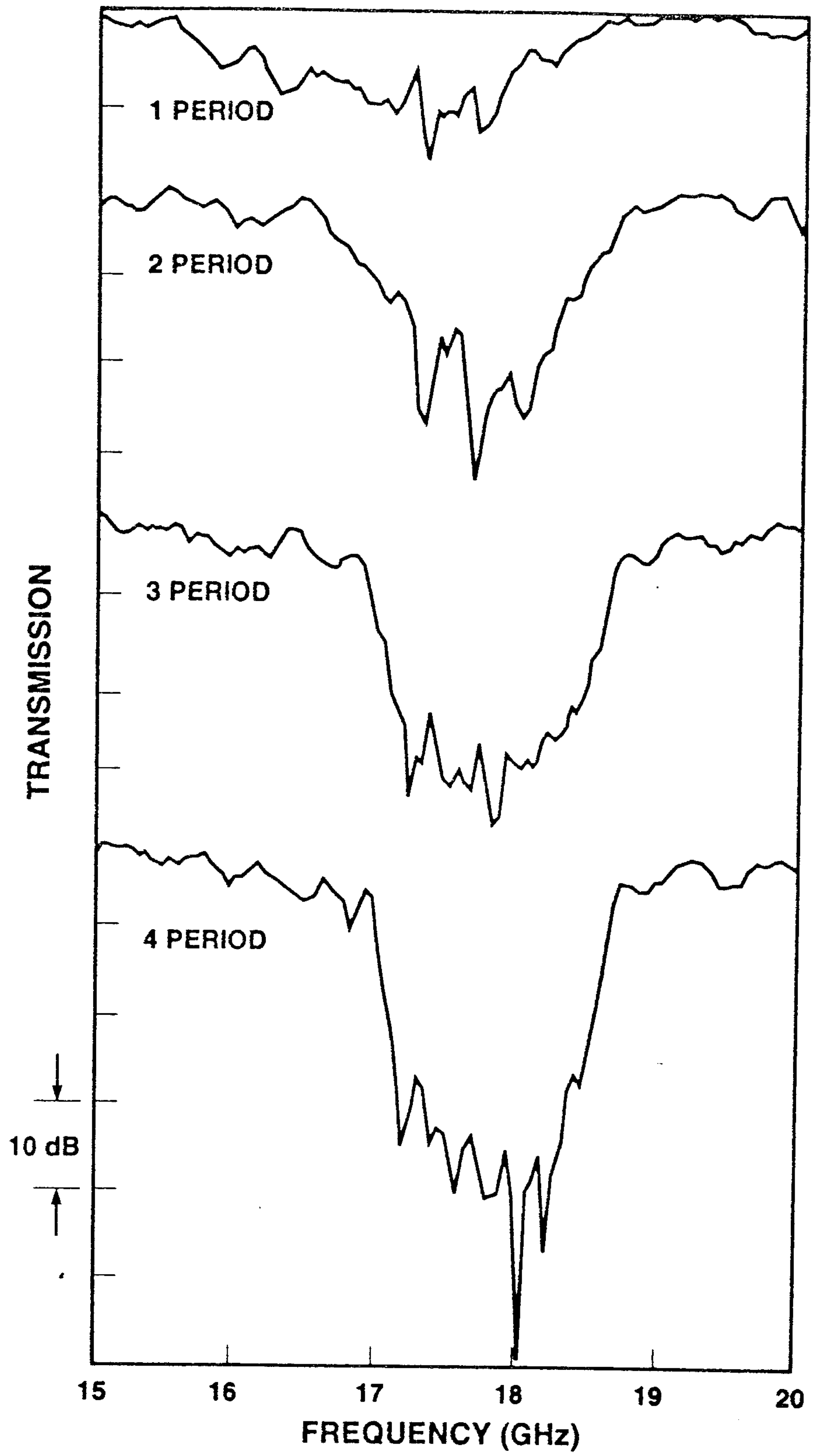

Fig. 2. Normal-incidence transmission ([111] direction of propagation) through one, two, three, and four repeat units of fcc photonic crystal.

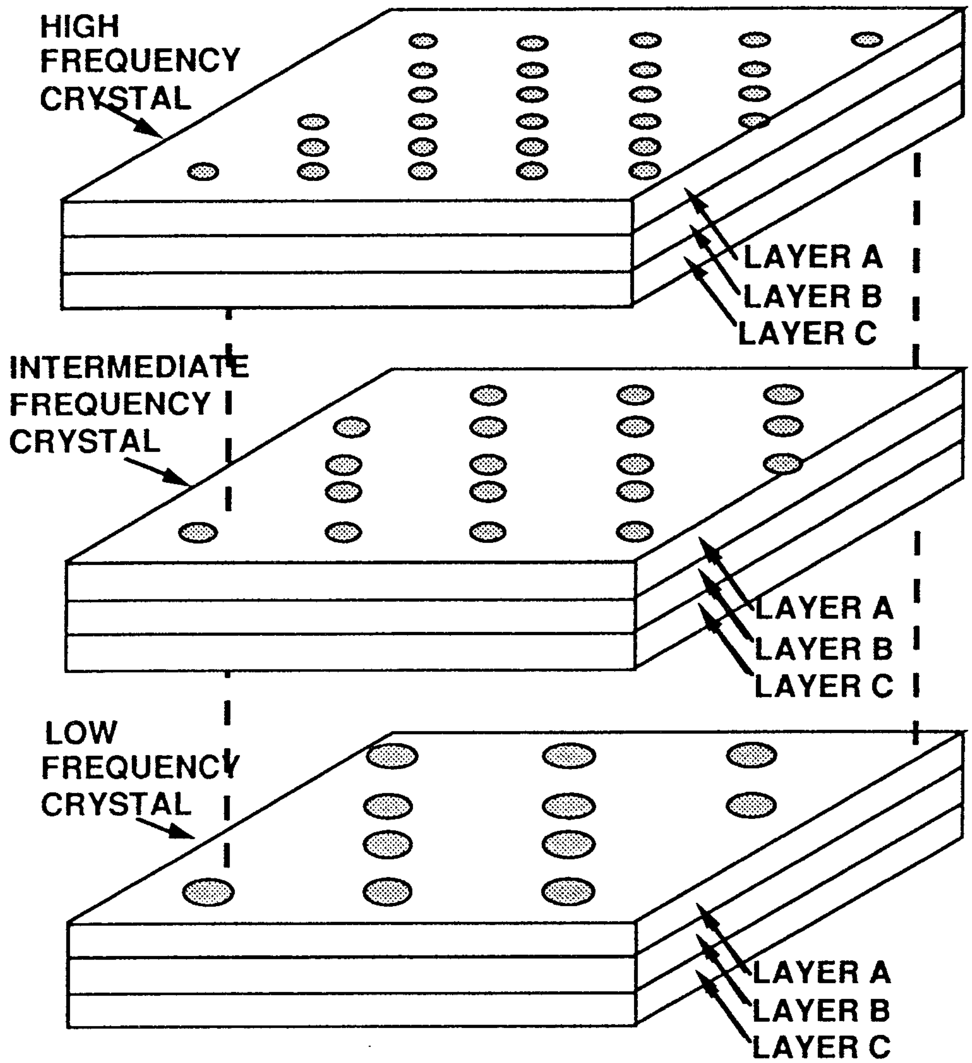

Fig. 3. Composite photonic crystal consisting of a vertical stack of monoperiodic sections of fcc crystal having different lattice constants.

2.1. Photonic-crystal heterostructure

To overcome the bandwidth limit, we have investigated a composite structure made by stacking monoperiodic sections of the (111)-oriented Lincoln-Lab fcc crystal, as shown in Fig. 3. Because of its similarity to semiconductor heteroepitaxial structures made from semiconductors having different band gaps, we call the resulting structure a photonic-crystal heterostructure. By making a discrete change in the lattice constant between adjacent monoperiodic sections, the net stop-band width can be increased well beyond that of a given section.

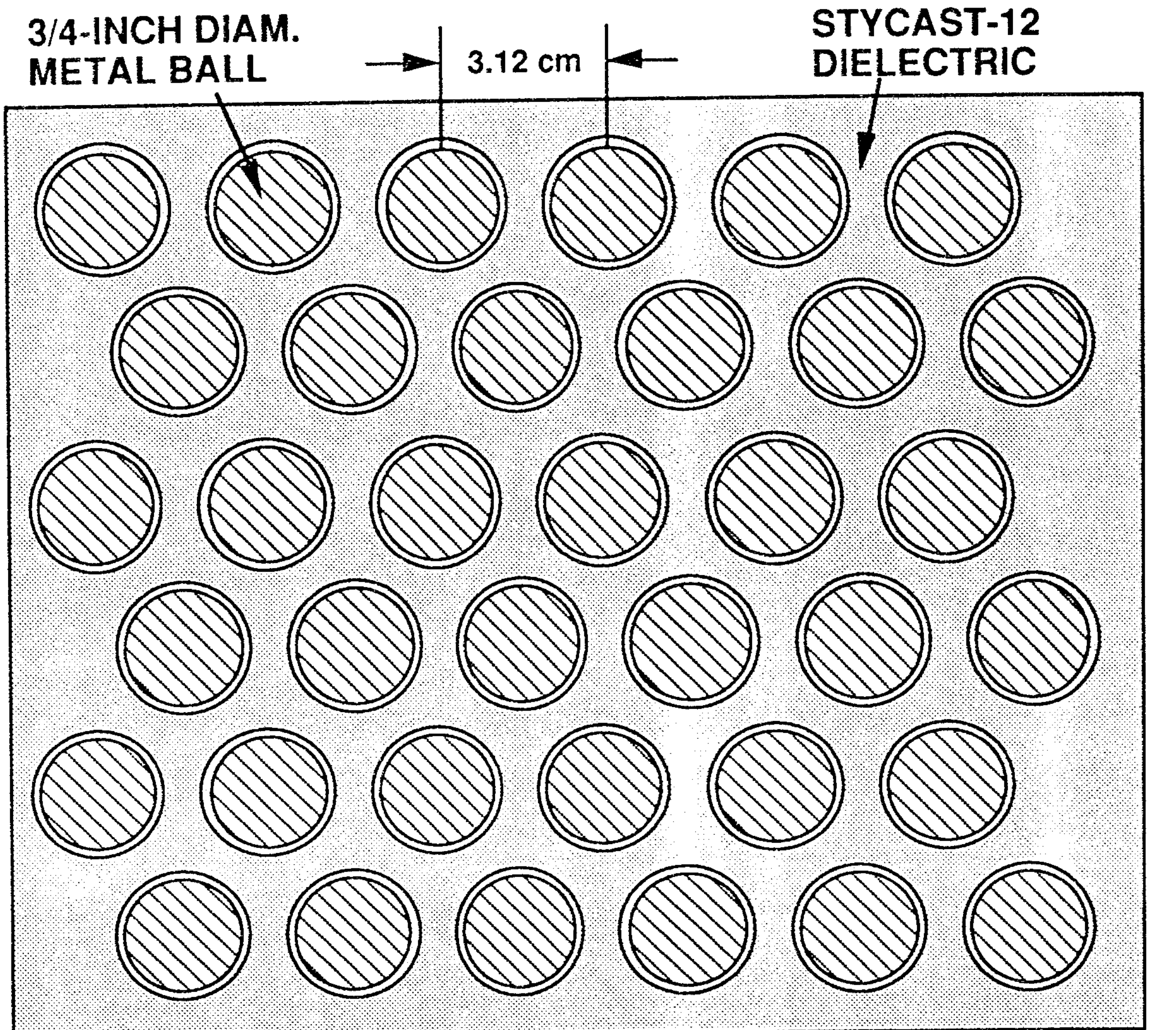

Fig. 4. Top view of metallodielectric photonic crystal showing the metal balls placed at each site of an fcc Bravais lattice oriented along the [111] direction. The dimensions and dielectric constant of the support material apply to the L-band crystal constructed for the Army Research laboratory and described in Sec. 3.2.

One of the features that makes the composite crystal attractive is the high transmission through the individual monoperiodic sections *outside* of the photonic band gap. This is exemplified in Fig. 2 where we see that the experimental transmission just below or above the band gap is generally above 50%. It means that the net reflection can be very high at frequencies within the band gap of sections lying well below the top of the composite structure. Without this property, standing waves would likely be established between the photonic-band-gap buried section and the partially reflecting upper layer or layers above it. This would lead to a resonant reflection at some frequencies, but very low reflection at others. Of course, such behavior would be undesirable for most applications.

2.2. Metallodielectric photonic crystal

To increase the rejection in the stop band, we implemented a metallic sphere as the atomic particle. Because of its large imaginary part of the dielectric constant, a metallic core can reflect radiation very efficiently, at least at microwave and millimeter-wave frequencies, if it is surrounded by lossless dielectric. The fcc lattice investigated in this work was constructed by stacking slabs (thickness s) of low-loss dielectric material, each slab containing a triangular lattice [lattice constant $t = (3/2)^{1/2}s$] of cylindrical air holes [7]. After fabricating the holes in each slab, chrome-plated steel spheres were inserted as shown in Fig. 4. Then the slabs were stacked in a closed-packed fashion with an "ABC" repeat unit, as shown in Fig. 1. In this way, the spheres in a given slab lie directly above the center of a triangular unit cell in the slab below, and spheres in two successive slabs occupy the two distinct close-packing possibilities of triangular lattices [6]. The resulting fcc structure has its (111) axis oriented along the stacking direction and has a conventional cubic lattice constant given by $a = 2^{1/2}t$.

We call the resulting structure a metallodielectric photonic crystal (MDPC) because, as will be shown below, the stop band characteristics depend strongly on the size of the metal spheres as well as the support dielectric constant. An important consideration in the MDPC is that the metallic spheres in adjacent layers do not touch physically. If they did touch, electromagnetic scattering from the connected spheres would likely be much different than from a single sphere and the sample would tend to act like a three-dimensional metal mesh structure. This is the structure that has recently been developed by Yablonovitch [8]. In a sense, our structure is the Babinet compliment of the metal-mesh crystal with the added feature of having a support material that can be selected over a large range of dielectric constant. More importantly, however, is the fact that unconnected atomic cores do not allow long-range conduction currents. Such currents contribute ohmic losses that increase rapidly with frequency and would make it difficult to operate photonic crystals in the infrared or visible regions.

3. ACCOMPLISHMENTS

The discussion of accomplishments on this program will be split into the three main areas of effort: (1) photonic crystal heterostructures, (2) metallodielectric photonic crystals, and (3) fabrication of photonic-crystal substrate for the Army Research Laboratory.

3.1. Photonic crystal heterostructure

3.1.1. EXPERIMENTAL RESULTS

A photonic crystal heterostructure consisting of three different sections of the Lincoln Laboratory fcc crystal was been constructed and tested in the range of 15 to 26 GHz. Each section was made from Stycast-10 sheets and had the fcc parameters listed in Table 1.

Table 1. Material parameters of three monoperiodic fcc sections in photonic crystal heterostructure.

Section	Slab Thickness	Triangular Lattice Constant	FCC Lattice Constant	Cylindrical Atom Diameter
Low	0.250 in.	0.306 in.	0.433 in.	0.250 in
Medium	0.228 in.	0.279 in.	0.395 in.	0.228 in.
High	0.200 in.	0.245 in.	0.347 in.	0.200 in.

Fig. 5(a) through (d) show the experimental transmission at normal incidence through the heterostructure, the high-frequency component crystal, the middle-frequency component crystal, and the low-frequency component crystal. The heterostructure has a maximum rejection of approximately 48 dB at 22.5 GHz, a minimum rejection of approximately 7 dB at 17.9 GHz, and a stop band that extends from 16 to at least 25 GHz. The low rejection at approximately 18 GHz occurs from too little overlap between the component band stops seen in Figs. 5(c) and (d). Clearly, the rejection of the heterostructure around 22.5 GHz is being assisted by the second stop band of the low-frequency crystal, as seen in Fig. 5(d). The fact that it is much deeper than the first stop band is typical for the Lincoln Lab fcc crystal.

Transmission measurements were also made with radiation incident on the photonic-crystal heterostructure away from normal incidence. Fig. 6 shows the net transmission measured with radiation incident at 35°, to be contrasted with Fig. 5(a). Surprisingly, the rejection is deeper at nearly all frequencies in the 15-to-25 GHz band than at normal incidence. In particular, the transmission leak at around 18 GHz in Fig. 5(a) is practically non-existent in Fig. 6. This suggests that the transmission leak is a standing wave resonance of the variety discussed in Sec. 2.2, since such resonances are strong only when the radiation propagates perpendicular to the

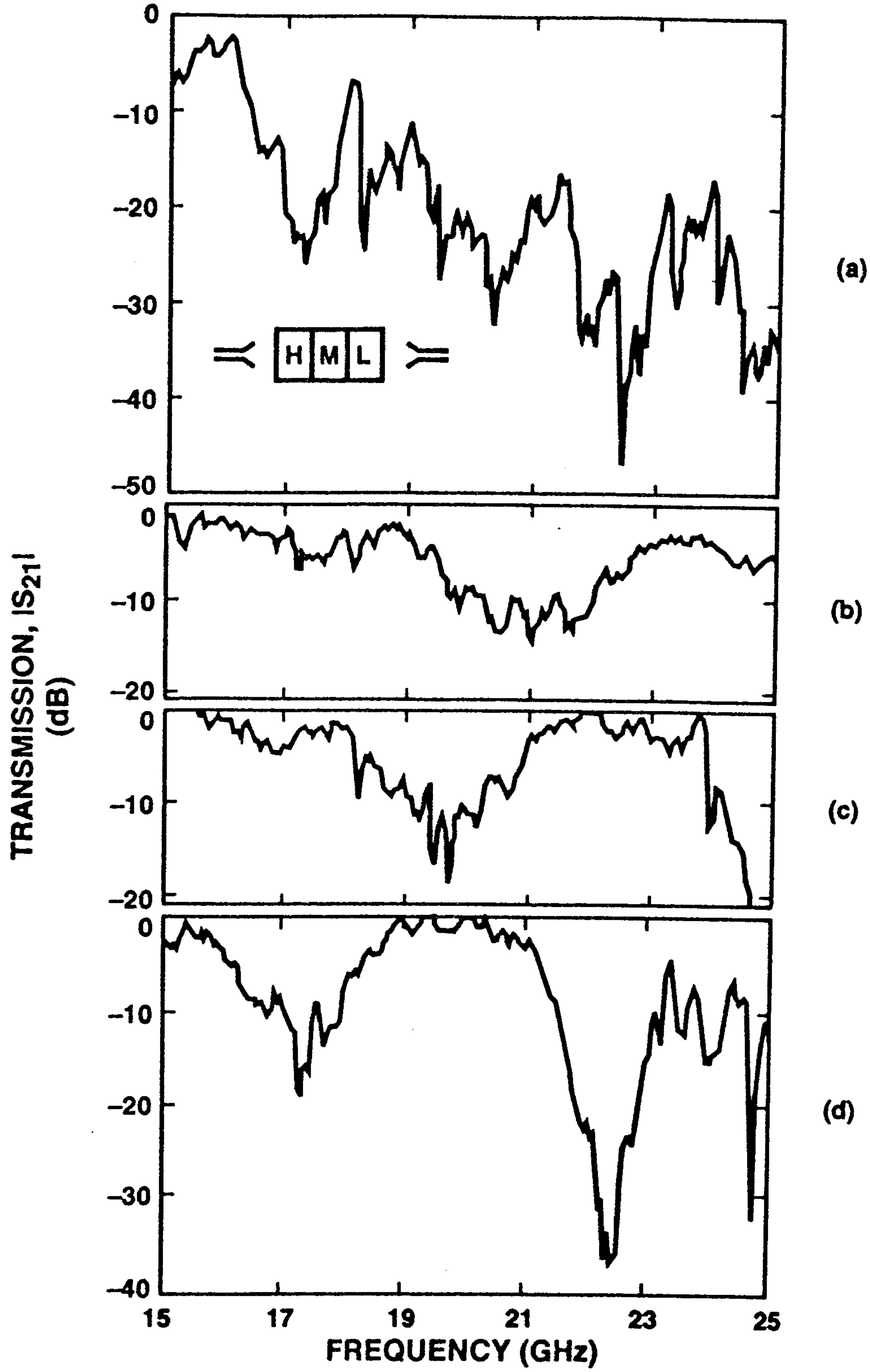

Fig. 5. Transmission through photonic-crystal heterostructure made from three monoperiodic fcc structures having slightly different lattice constant, as described in Table 1.

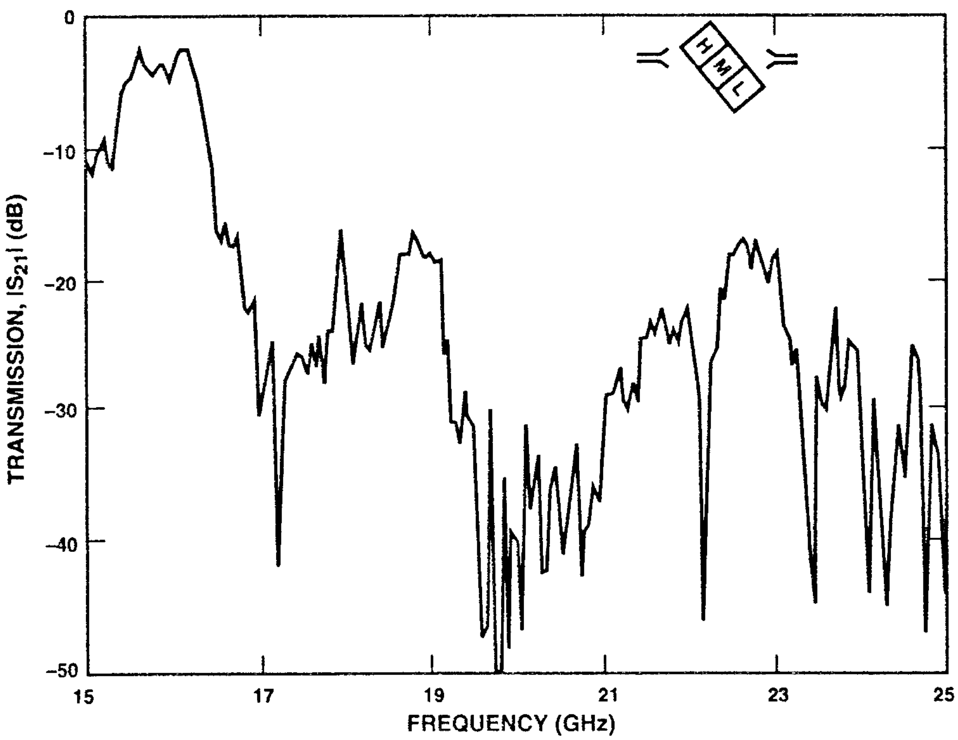

Fig. 6. Transmission through three-section photonic crystal heterostructure at 35° angle of incidence.

planes of reflection such that multiple-pass interference occurs.

3.1.2. DISCUSSION

Initially, it was somewhat surprising that resonant transmission did not play a greater role in the experimental results. From the behavior of optical and microwave etalons, it was expected that large standing waves would be generated between adjacent sections around the frequency where the reflection of the sections was equal. However, the photonic crystal sections are acting like *distributed* reflectors, not the planar or quasi-planar reflectors that one encounters in etalons. Therefore, the build-up of standing waves between the sections is actually rather weak and the resonant transmission is well below unity.

Because of the lack of strong internal interference, one can approximate the net reflection from the heterostructure by the following scalar formula

$$R_T \approx R_1 + T_1R_2T_1 + T_1R_2^2R_1T_1 + T_1R_2^3R_1^2T_1 + \ldots = R_1 + \frac{T_1^2R_2}{1-R_1R_2} \qquad (1)$$

where R_1 (T_1) and R_2 are the reflections (transmissions) from the upper and lower monoperiodic section, respectively, associated with each intersection.

3.1.3. DESIGN CRITERION

From our work on the photonic-crystal heterostructure, the following simple design criterion has been formulated. Independent of the number of monoperiodic sections in the overall structure, the center frequencies of the stop bands in adjacent sections should be offset such that they are contiguous (i.e., intersect at approximately the half-reflection frequencies). Assuming that the band gap of each section has a constant fractional width δ about the center frequency, one can then derive (by mathematical induction) the following expressions for the overall fractional width Δ,

$$\Delta = \frac{(1+\delta/2)^N - (1-\delta/2)^N}{(1+\delta/2)^N + (1-\delta/2)^N}, \tag{2}$$

and the ratio r of the maximum and minimum frequencies of the overall band gap,

$$r = \frac{(1+\delta/2)^N}{(1-\delta/2)^N}, \tag{3}$$

The values of r for various values of N are listed in Table 2 assuming a δ of 15% (the measured width of our $\eta = 0.60$ fcc crystal). Notice that a gap width of over one octave ($r = 2$) can be obtained with just 5 sections and over two octaves with 10 sections.

Table 2. Ratio of maximum to minimum frequency of the stop band of a composite structure consisting of N sections of monoperiodic photonic crystal, each having $\delta = 15\%$.

N	1	2	3	4	5	6	7	8	9	10	11	12
r	1.16	1.35	1.57	1.82	2.12	2.46	2.86	3.33	3.87	4.49	5.22	6.07

3.2. Metallodielectric photonic crystal

3.2.1. EXPERIMENTAL RESULTS

Stycast MDPC samples

To facilitate the fabrication, we made our first MDPC sample from the same 1/4-inch-thick Stycast slabs used to make one of our fcc structures with air atoms. Three sheets were used having dimensions 0.64×15.2×15.2 cm (0.25×6.0×6.0 inch). The cylindrical-atom diameter in each slab was 0.25 inches. The fcc structure without metal spheres also served as a control sample in microwave transmission measurements.

After fabrication, the microwave transmission through the MDPC and control samples were measured from 5 to 26 GHz with an HP 8510 network analyzer. A set of three feedhorns was used to transform the radiation from coaxial cable to free space: a C-band horn covering 5 to 10 GHz, a Ku-band horn covering 10 to 18 GHz, and a K-band horn covering 18 to 26 GHz. Each horn was used only within the stated range to ensure Gaussian-like beam characteristics and linear polarization incident on the sample. Feedhorns are useful in this experiment because they create a beam larger than a few lattice constants but smaller than the lateral extent of the sample. The crystals were oriented so that the radiation propagated along the [111] axis of the conventional cubic unit cell. Therefore, a frequency sweep with the network analyzer corresponds to a variation of wave vector along the locus connecting the Γ and L points in the fcc Brillouin zone.

Fig. 7 compares the transmission of the 1/4-inch Stycast MDPC sample and the photonic crystal control sample. Each is plotted in comparison to the transmission between feedhorns through air. The control sample shows a transmission relative to air of near unity up to approximately 16.5 GHz (at some frequencies the free-space transmission is lower than the photonic-crystal transmission because the sample tends to focus the beam somewhat). At higher frequencies, there is a 5-to-10-dB-deep stop band extending from approximately 16.5 to 19 GHz. At even higher frequencies centered around 22.5 GHz, there is an upper stop band that has higher rejection than the first one. Both of these features are consistent with separate measurements made on a thicker sample having the same fcc structure, and are consistent with Bragg scattering in the usual sense.

In contrast, the MDPC sample shows a wide and deep stop band that starts at approximately 5.5 GHz and extends up to approximately 12 GHz. Aside from the undulations, the average rejection across this band is approximately 20 dB, which corresponds to 11.5 dB per cubic lattice constant. Above 13 GHz the MDPC returns to near-100% transmission, displays some localized dips, and then falls into another deep stop band starting at about 19 GHz. Two aspects of the MDPC transmission are quite remarkable. First, the width of the first stop band Δf

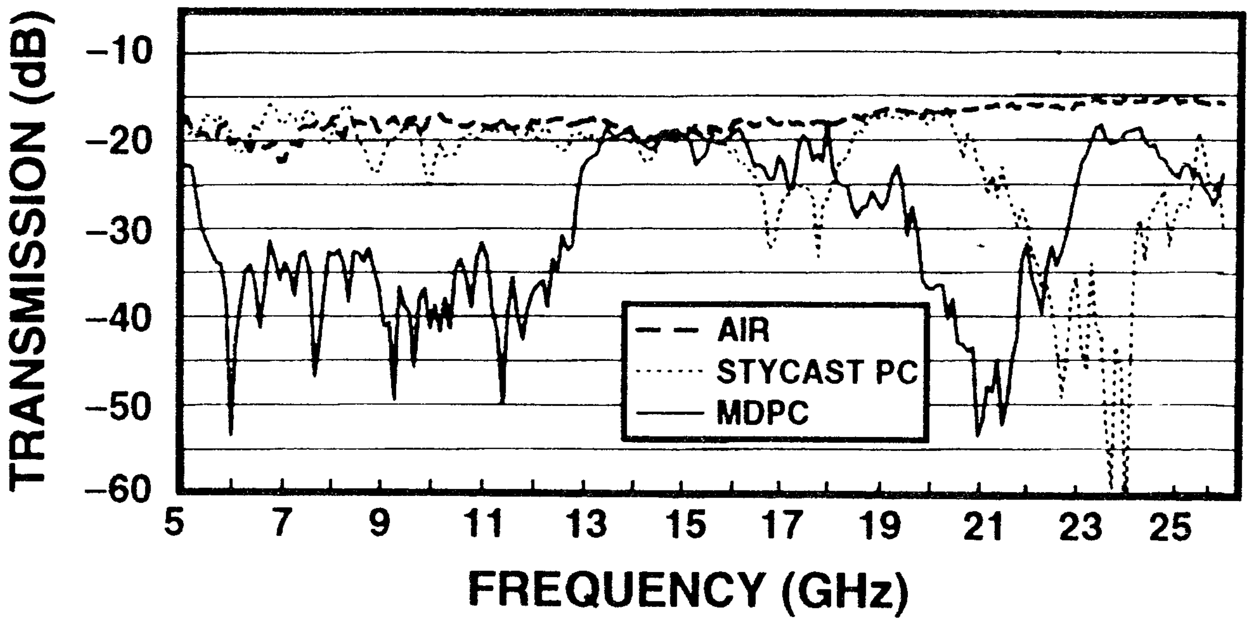

Fig. 7. Normal-incidence ([111] direction) transmission through a conventional fcc photonic crystal (cylindrical air holes) and a MDPC sample made by adding to each cylinder of the conventional crystal a chrome-plated metal sphere. The transmission of both samples is referenced to the transmission through free space.

of approximately 74% about the center frequency f_C represents at least a four-fold increase over $\Delta f / f_C$ in any previous photonic crystal known to the authors. This is very important for microwave applications, which are beginning to require at least one octave ($\Delta f / f_C = 0.67$) of operating range. Second, the transmission through the MDPC below and just above the first stop band approaches very close to unity. This is not surprising for the conventional photonic crystal in Fig. 2 since it consists mostly of air. In the MDPC, however, the crystal is mostly metal which, in the form of a slab having the same lateral dimension, would reflect over 99% of the incident radiation in the given frequency range.

To determine if the band stop was three dimensional, the transmission characteristics of the MDPC were measured along three other propagation directions in the conventional cubic unit cell: (100), (1,1/2,0), and (110). These directions correspond to loci connecting the following points in the fcc Brillouin zone: (1) Γ to X, (2) Γ to W, and (3) Γ to K. In each case, a band stop was observed, but shifted up in frequency relative to that measured along the (111) direction. The overlap in frequency between these four stop bands and those measured along all other propagation directions, which defines the photonic *band gap*, is still being analyzed.

Teflon MDPC samples

After observing the transmission through the Stycast MDPC sample, we hypothesized that high dielectric-constant material may be unnecessary since the real part of the dielectric constant of the chrome (or any good conductor) is close to zero. The important factor is probably the large imaginary part of the dielectric constant of the metal, which also the determines the reflectivity of metal in bulk form. Therefore, we pursued MDPC samples make from the plastic Teflon ($\varepsilon = 2.1$). This material was also chosen because it is much cheaper and simple to fabricate than Stycast. The Stycast has similar dielectric characteristics to semi-insulating GaAs ($\varepsilon = 12.8$) and high-resistivity silicon ($\varepsilon = 11.9$), which are both useful materials for microwave and millimeter-wave integrated circuits. The Teflon has similar characteristics to certain polymers that are of great interest in scaling the MDPC to much shorter wavelengths.

Three Teflon fcc structures were made: one with 1/4-inch-thick slabs and 3/16-inch-diameter spheres, the second with 1/4-inch-thick slabs and 1/4-inch-diameter spheres, and the third with 3/8-inch-thick slabs and 3/8-inch-diameter spheres. In all cases, the metal spheres were chrome-plated steel balls that were dropped into each cylindrical core during the slab-stacking procedure.

The plot in Fig. 8(a) shows the transmission through the first sample having 1/4-inch thick slabs and 1/4-inch-diameter spheres. Aside from two narrow dips between 6 and 8 GHz, the transmission is dominated by a broad stop band that starts at approximately 9 GHz and extends up to approximately 22 GHz. This represents a $\Delta f / f_c$ of 0.84, even wider than the Stycast MDPC band stop. Ignoring the oscillations in the band, we find a maximum rejection within the stop band of roughly 15 dB (9 dB per cubic lattice constant). This is comparable to the rejection of the best conventional photonic-crystal samples.

Fig. 8(b) shows the transmission of the second Teflon MDPC sample having 1/4-inch-thick slabs and 3/16-inch-diameter spheres. Like the first sample, the transmission is dominated by a stop band starting at about 14 GHz and extending up to about 22 GHz. In addition, there are some smaller rejection features lying between about 8 and 10 GHz. The maximum rejection in the broad stop band is roughly 12 dB (7 dB per cubic lattice constant). This is comparable to the rejection in rather poor conventional photonic crystals. Nevertheless, the transmission is intriguing in the sense that the upper edge of the stop band is practically identical in frequency to that of the first Teflon MDPC sample, whereas the lower edge has increased in frequency by over 50%. As we will discuss further below, this suggests that metallic core scattering is dictating the frequency of the lower band edge.

To test the effect of lattice periodicity and core dimension simultaneously, we fabricated and tested a third Teflon MDPC sample consisting of 3/8-inch-thick Teflon slabs and 3/8-inch metal spheres. The resulting transmission is plotted in Fig. 8(c). In this case, there is a very

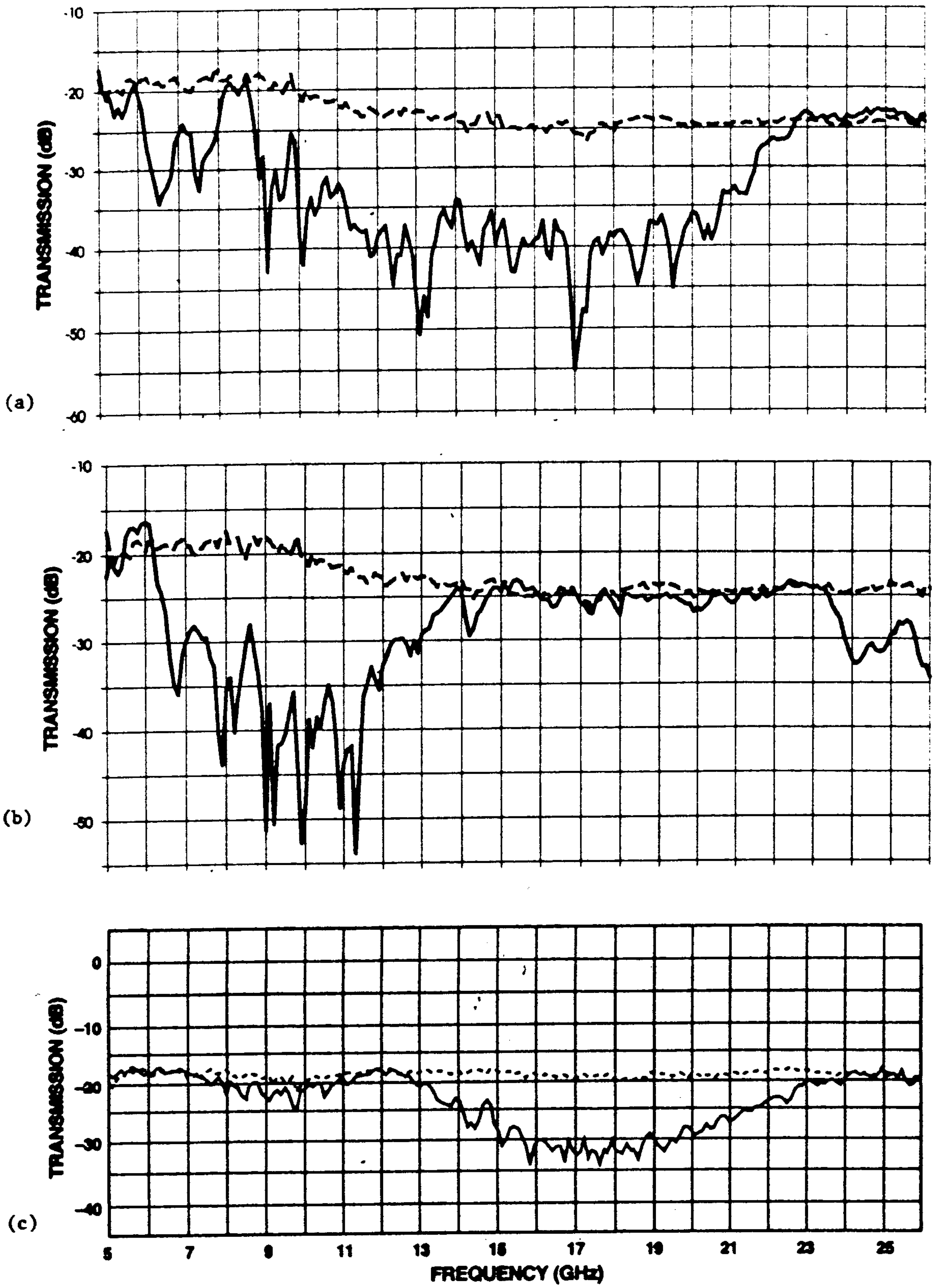

Fig. 8. Normal-incidence transmission through three Teflon fcc MDPC samples. (a) 1/4-inch-thick Teflon slabs with 1/4-inch-diameter metal spheres. (b) 1/4-inch-thick Teflon slabs with 3/16-inch-diameter metal spheres. (c) 3/8-inch-thick Teflon sheets with 3/8-inch-diameter metal spheres.

precipitous onset of a stop band starting at approximately 6.5 GHz and extending up to roughly 13 GHz. The maximum rejection in the stop band is roughly 20 dB, similar to the Stycast MDPC sample. Again, the transmission gets very close to unity just below and above the stop band. The other significant rejection feature in the 5-to-26-GHz range is onset of a second apparent stop band starting at approximately 23.5 GHz.

3.2.2. DISCUSSION

Intuitively, we expect that the broad rejection of the MDPC samples must be related to the fundamental differences in electromagnetic scattering between dielectric and metallic atomic cores. In the simple case of spherical geometry, it is well known from work early in the 20th century that dielectric and metallic spheres both exhibit little effect on electromagnetic radiation at wavelengths much greater than the diameter of the sphere. As the wavelength decreases, both types of spheres begin to scatter much more efficiently. In fact, the scattering cross section σ varies with wavelength as $1/\lambda^4$ according to Rayleigh's well-known relation. What differentiates dielectric from metallic spheres is the strength and direction of the scattering. For a dielectric sphere, the total amount of scattering at a given wavelength is always much weaker than for a metal sphere of the same diameter. Furthermore, the work of Mie showed that at wavelengths just greater than the sphere diameter, most of the scattered radiation from dielectric spheres occurred into the forward hemisphere [9]. In contrast, at the same wavelength condition on metallic spheres, most of the scattering occurs into the reverse hemisphere, even though there is a small Mie effect.

Another relevant result of Mie's work was that the scattering cross section approaches a maximum when the wavelength satisfies the condition, $\pi D/\lambda \approx 1$, where $\lambda = \lambda_0/n$ is the wavelength in the dielectric medium (refractive index n) immediately surrounding the sphere, and λ_0 is the wavelength in free space. For example, we consider the Teflon MDPC demonstrated in Fig. 7(a) in which D = 0.25 inch, and $n = (2.1)^{1/2}$. In this case, we find a Mie frequency of $c/\pi Dn$ = 10.4 GHz. This is obviously in good agreement with the measured low-frequency edge of the stop band.

3.3. Fabrication of L-band MDPC Sample for the Army Research Laboratory.

In addition to the bandwidth issue, another reason for devising the MDPC material was the need to get more rejection per unit length of photonic crystal than could be achieved in conventional structures. This need was particularly acute in a task carried out under this program that entailed the construction of an antenna substrate for the frequency region between 1 and 2 GHz (L band). This task was commissioned by Lou Jasper of the Army Research Laboratory in Adelphi Maryland. To get a band stop in this frequenay range with either

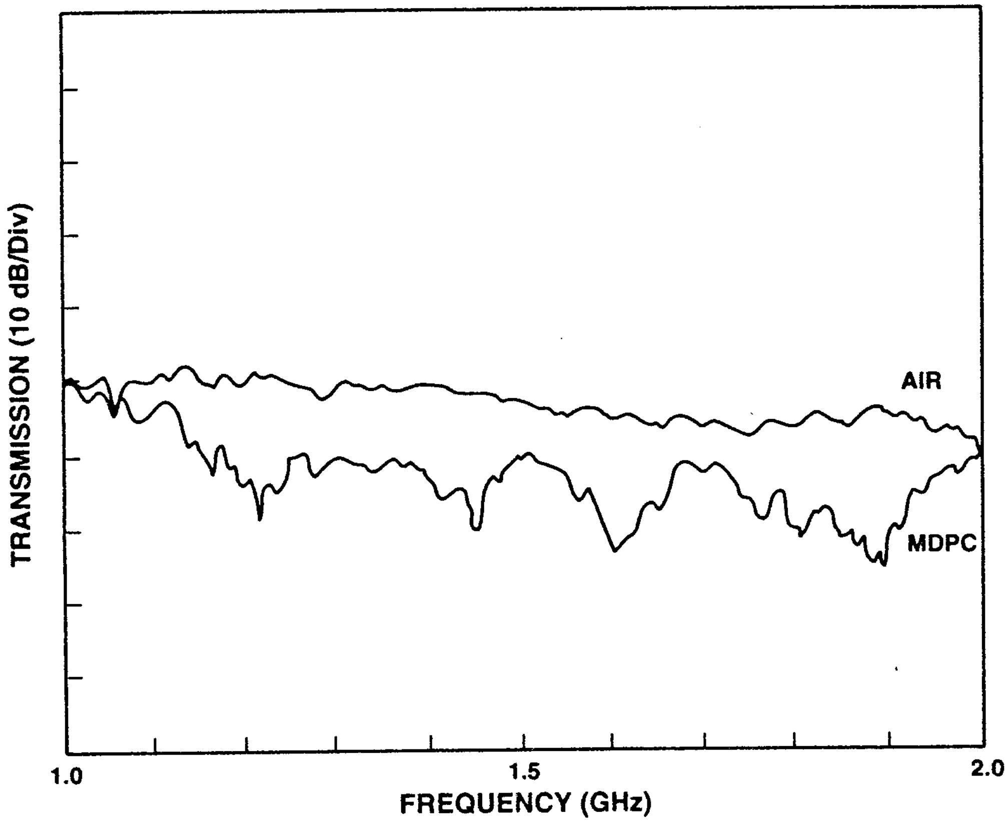

Fig. 9. Metallodielectric photonic crystal manufactured for the 1-to-2 GHz range. The material dimensions of the sample are given in Fig. 4.

conventional photonic crystals or the MDPC structures required, it was necessary to incease the fcc lattice period to over one inch. This meant that the Stycast slabs making up the dielectric portion of the crystal would have to be at least one inch thick and one foot wide. In this case, a conventional photonic crystal structure having three repeat units would be at least nine inches thick. The volume of the crystal was considered prohibitive, not to mention the cost of the Stycast and the difficulty of fabrication.

To operate in the 1-to-2 GHz range, an MDPC sample was designed by scaling down the dimensions of the sample used for Fig. 7. The size of the Stycast-12 slabs were 1x1 foot wide by 1-inch thick. The metal ball diameter was 0.75 inch, the triangular lattice constant was 1.22 inch (3.12 cm), and the fcc lattice constant was 1.73 inch (4.40 cm). A top view of the resulting structure is shown in Fig. 4. The microwave transmission was measured in the 1-to-2 GHz range using large pyramidal feedhorns in conjunction with an H.P. 8510 network analyzer. The resulting transmisison spectrum is shown in Fig. 9. Clearly, there appears to be a low-frequency band edge starting at approximately 1.15 GHz, and an upper-frequency edge at about 1.9 GHz.

1.9 GHz. The rejection in the band stop oscillates between about 5 and 10 dB, substantially less than the rejection for the Stycast MDPC sample of Fig. 7. The reason for this discrepancy is not entirely clear, but the finite lateral extent of the sample is suspect. Although the lattice parameters of the MDPC of Fig. 7 were scaled up a factor of four, the lateral dimension was only increased two times. Hence at the 1-GHz operating frequency, the ratio of sample width to free-space wavelength was only unity, compared to 2.5 times for the lowest test frequency in Fig. 7. With the sample width comparable to the wavelength, it is likely that radiation leaks around the sample by diffraction and edge effects, making the measured rejection less than the the actual rejection.

4. REFERENCES

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5. PROFESSIONAL PERSONNEL

Over the course of this program, the following personnel were involved to some degree in the research effort:

Name	Contribution
Elliott R. Brown	Photonic crystal design, testing, and analysis. Program management.
Oliver B. McMahon	Wideband photonic crystal fabrication and testing
Kamil Agi	Photonic crystal heterostructure concept, fabrication, and testing.
Christopher D. Parker	Photonic crystal fabrication and testing

Mr. Agi is a graduate student working on his Ph.D. thesis at the University of New Mexico under Professor Kevin Malloy. Mr. Agi is supported by an AASERT grant through the Air Force Office of Scientific Research.

6. TECHNICAL INTERACTIONS

6.1. CONFERENCE PAPERS

The following is a list of presentations given by the above personnel in the period 1 January 1994 through 30 September 1995 on subjects relevant to this program:

"Metal/Dielectric Hybrid Photonic Crytals," to be given at 1995 Annual Meeting of the Optical Society of America, Portland, OR, 10-15 Sept. 1995.

"Microwave Applications of Photonic Crystals," presented at the NATO Advanced Research Workshop on Photonic Crystals, Crete, Greece, 19-29 June 1995.

"Microwave and Millimeter-Wave Applications of Photonic Crystals," 1995 March Meeting of the Americal Physical Society, San Jose, CA, 22 March 1995.

"Novel Devices for Terahertz Generation and Radiation," Fifth International Symposium on Space Terahertz Technology, Ann Arbor, MI, 10 May 1994.

"Photonic-Crystal Planar Antennas for Millimeter Wavelengths," International Semiconductor Device Research Symposium, Charlottesville, VA, 3 Dec. 1993.

6.2. SEMINARS

University and government seminars have been given under the support of this program.

Host Institution (Location, Date)	Technical Emphasis
U.S. Army Missile Command (Redstone Arsenal, Alabama, Feb. 1995)	Photonic Crystal Materials and Antenna Applications
Iowa State University (Ames, Iowa, Feb. 1995)	Microwave and Millimeter-Wave Applications

6.3. COLLABORATIONS

Over the course of this program, the following collaborations have been established with organizations outside of Lincoln Laboratory. They included both industrial collaborations and interactions with other government labs and academic institutions:

Organization (Time Period)	*Technology*	*Collaborator*
Bellcore and UCLA (1992 -)	Comparison of fcc photonic crystal structures	Prof. Eli Yablonovitch
Ames Laboratory/Iowa St. University (1995 -)	Submillimeter-wave spectroscopy of defect modes in diamond woodpile photonic crystals	Prof. K-M. Ho, Prof. Gary Tuttle
MIT Physics Department	Band structure computations of MDPC structures	Prof. John Joannopoulos

7. PUBLICATIONS

The following list of manuscripts has appeared in press or is in the process of being reviewed for a scientific journal.

"Observation of large electromagnetic stop band in metallodielectric photonic crystals," E. R. Brown and O. B. McMahon, submission to Phys. Rev. Lett., June 1995.

"Microwave and millimeter-wave applications of photonic crystals," E. R. Brown, Bull. Am. Phys. Soc., vol. 40, p. 491 (1995).

"Design of ultrawideband photonic crystals for broadband antenna applications," K. Agi, E. R. Brown, O. B. McMahon, C. Dill III, and K. J. Malloy, Electron. Lett., vol. 30, 2166 (1995).

"An ultrawideband photonic crystal," K. Agi, E. R. Brown, C. Dill III, O. B. McMahon, and K. J. Malloy, in *Ultra-Wideband Short-Pulse Electromagnetics 2*, ed. by H. L. Bertoni, L. Carin, and L. B. Felsen (Plenum, New York, 1995).

"A new face-centered-cubic photonic crystal for microwave and millimeter-wave applications," E. R. Brown, K. Agi, C. Dill III, C. D. Parker, and K. J. Malloy, Microwave and Optical Tech. Lett., vol. 7, 777 (1994).